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Urban climate multi-scale modelling in Bilbao (Spain): a review

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Abstract

Despite development of cities are including more sustainable aspects (e.g. reduction of energy consumption), urban climate still needs to be consolidated as an important variable in urban planning. In this sense, the analysis of urban climate requires a multi-scale approach. This work presents a review of the results of the analysis of urban climate in Bilbao (Spain). In the meso-scale, an Urban Climate Map (UC-Map) is developed using a method based on GIS calculations, specific climatic measurements and urban climate expert knowledge. All the information is grouped in 5 information layers (building volume, building surface fraction, urban green areas, ventilation paths and slopes). The final UC-Map presents areas with relative homogeneous climate variables (i.e. climatopes) that are classified in terms of thermal comfort. Urban planning recommendations are defined. In the micro-scale, results extracted from ENVI-met model in four urban spaces show the influence in thermal comfort levels of the interaction of regional climate conditions with the urban development characteristics of each area and the location inside the whole city. In both spatial scales, climate modelling should be accompanied by specific measurement campaigns to validate results.

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Keywords: urban climate; thermal comfort; urban planning; modelling; measurements

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1. Introduction

During the 20th century urban development has experienced a tremendous growth producing a significant alteration of the natural environment. Thus, urban areas have lost the necessary ecological balance with the surroundings.

Two are the more significant effects of urban areas in the climate: a) an alteration of local winds and turbulence, and b) an increase in temperature compared to rural surroundings, known as Urban Heat Island [1].

Additionally, nowadays one of the major environmental problems is climate change and the urban areas are known to be very vulnerable to this phenomenon. Thus, thermal comfort inside urban areas can be seriously affected in the future [2–4]. However, until the last three decades urban climate knowledge was rarely applied in urban planning [5].

The work presents a review of the results of a multi-scale analysis of the urban climate and thermal comfort in Bilbao urban area. This approach is necessary to provide climate information to urban planners and decision-makers in a suitable way so that they can use it for planning purposes. In each spatial scale, different information is presented, and the approach and tools to undertake the urban climate analysis are different.

2. Methodology

Two different spatial scales are defined to analyse urban climate and thermal comfort. These are the urban and local scale, i.e. mesoscale and microscale (Fig 1). Not only they describe and highlight the relevant physical process at each scale but also account for the different urban planning scales (whole city and local planning). In each spatial scale a different approach is used. These are presented in the following sub-sections.

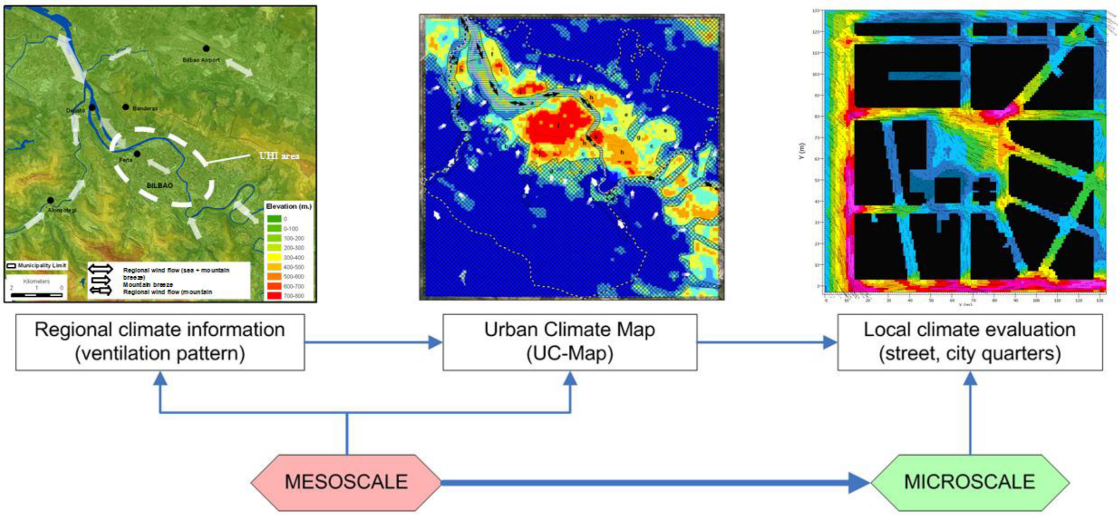

Fig 1. Multi-scale approach of urban climate. Steps to evaluate climate in an urban planning context

2.1. Meso-scale

An Urban Climate Map (UC-Map) was developed to include climate information from the regional to the urban scale. At this scale, the analysis of regional climate affecting the urban area was essential to define the ventilation pattern in the urban area. The UC-Map mainly consisted of two maps. One is the Urban Climate Analysis Map (UC-AnMap) and the other is the Urban Climate Recommendation Map (UC-ReMap). The UC-AnMap included climate information describing UHI effects and ventilation patterns. It defined and evaluated areas with specific climate characteristics that have similar impact on thermal comfort. These areas are known as climatopes. The UC-ReMap included urban planning instructions to improve or protect climate in different areas of the city.

For Bilbao UC-Map an 8.7 x 8.4 km. domain was defined with a 100 m. resolution, covering all the municipality area.

The method used to develop the UC-AnMap was based on calculations made with different GIS layers, climate measurements and urban climate expert knowledge [6]. The GIS layers included information of the physical variables affecting the urban climate. The combination these with adequate weighting factors allowed analyzing the thermal load and dynamic potential in the urban area of Bilbao and thus its effect on the climate and thermal comfort in different areas of the city. All the necessary data and information was included in five GIS layers (Fig. 2):

- Building volume: affecting heat storage capacity
- Building surface fraction: describing the effect on heat storage and ventilation due to urban permeability to wind
- Green areas: affecting surface heat balance and vegetation cooling potential
- Ventilation paths: describing local to regional ventilation properties influenced by surface roughness and topographical structures
- Slopes: describing the effect of increasing ventilation due to urban permeability to background winds, and development of thermal induced circulations

To evaluate ventilation properties of the urban area (e.g. regional winds and local circulations patterns), a previous analysis of the regional climate was mandatory. Finally, the use of climate measurements in different areas of the city allowed validating the GIS calculations and thus the UC-AnMap (Fig. 2). Both for the analysis of urban ventilation properties and the selection of sites and evaluation of the measurements, urban climate expert knowledge turned out to be important.

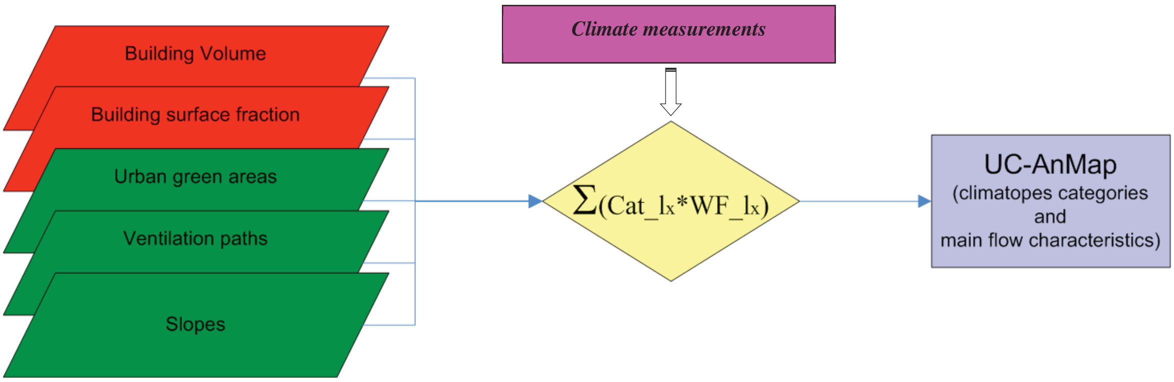

Fig 2.. Combination of GIS layers with weighting factors based on measurements3.2 Description of regional climate [6]

2.2. Micro-scale

To evaluate climate at scales from the street to city quarter level, micro-scale analysis were performed [7]. Four urban areas with different local climate (due to different the urban development type and the exposure to influence of regional climate) were selected inside the city. Their location can be seen on Fig. 3. *Ribera* is located in an open-set area beside the river waterway (i.e. the most important ventilation path that crosses through the middle of the urban area); *Miribilla* is in an open-set highrise urban development in one of the most elevated areas of the city; *CascoViejo* is in a very dense urban development (i.e. compact lowrise); and *Indautxu* is in a compact midrise district in the city centre. Further analysis of Bilbao UHI the land use classification can be found at Acero et al. [8].

Detailed micro-scale climate modelling was performed to analyze climate variables and thermal comfort spatial distribution. In this case, ENVI-met model (version 4) was used. This is a three-dimensional non-hydrostatic microclimate model developed to calculate and simulate climate variables in urban areas with a typical grid resolution of 0.5 to 10 meters. The model considers a complete radiation budget (i.e. direct, reflected and diffused solar radiation and longwave radiation). It models the evolution of climate variables during diurnal cycles using laws of fluid dynamics and thermodynamics. The ENVI-met software calculates the state of the atmosphere by combining the influence of buildings, vegetation, surfaces characteristics, soils and climatic contour conditions [9,10].

The results were compared with local climate measurements carried out during three days (6th to 8th August 2010) in typical summertime weather (i.e. influence of sea breeze) using mobile devices from sunrise to sunset. Measured data were: air temperature (Ta), relative humidity (RH), wind speed (WS), wind direction (WD) and globe temperature (Tg). Specific sites for measuring inside the four areas were selected considering urban climate expert knowledge. Mobile sensors were moved from one site to another during the campaigns. The period in each measuring site (i.e. >15 minutes) was appropriate to record representative data and evaluate microclimate conditions. For Tg calculation, the method tested for outdoor conditions was used [11,12]. The whole measuring system recorded 1 minute average values at 1.1 meter a.g.l. Mean radiant temperature (Tmrt) was derived from the previous measurements following the equation presented in Thorsson et al. [11]. At each site, with the aim of obtaining representative measured data, 10-minute mean values were calculated [11] for all the climate parameters (Tmrt, WS, Ta, RH, WS).

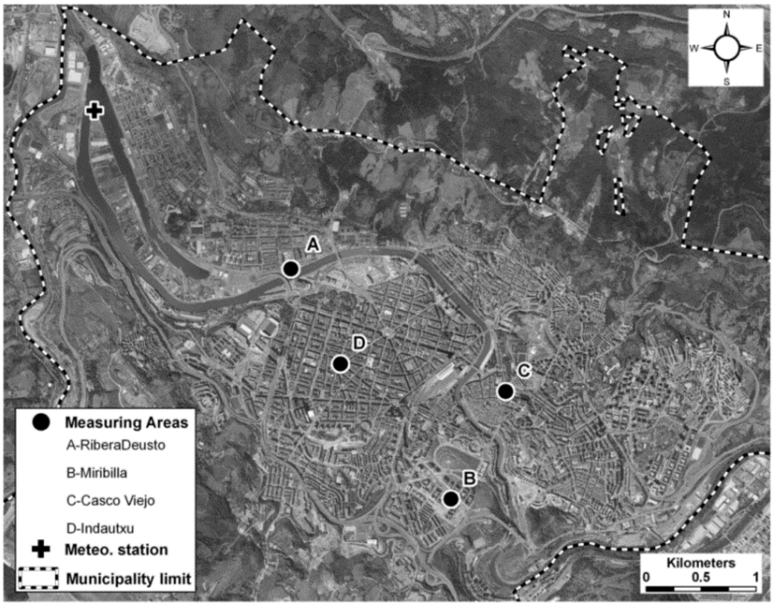

Fig. 3 Location of the measuring areas during the campaigns in Bilbao. Location of Deusto station (Basque Meteorological Agency)

Thermal levels were assessed by means of the Physiological Equivalent Temperature (PET) Index [13]. Table 1 shows the relation between PET values and thermal perception and level of stress. Thus, Ta and RH conditions as well as radiation and wind data (i.e. Tmrt and WS) were required both from the measurements and micro-scale modelling.

The daytime thermal comfort evolution and the levels reached in typical summertime in Bilbao were evaluated together with the differences between the four areas.

Table 1 Range of PET index values for thermal perception and level of physiological stress [14]

PET (ºC)	Thermal perception	Level of stress
< 4	Very cold	Extreme cold stress
4-8	Cold	Great cold stress
8-13	Cool	Moderate cold stress
13-18	Slightly cool	Slight cold stress
18-23	Neutral/Comfortable	No thermal stress
23-29	Slightly warm	Slight heat stress
29-35	Warm	Moderate heat stress
35-41	Hot	Great heat stress
>41	Very hot	Extreme heat stress

3. Results

3.1. The Urban Climate Map (UC-Map)

In the case of the UC-AnMap, different categories and the weighting factors for each GIS layer were selected considering urban climate expert knowledge and the measured climate data in different areas of the city. These values are presented in Table 2. The weighting factors applied to each GIS layer were reasonable regarding its effect on the urban climate in Bilbao and thus the thermal comfort perceived.

Table 2. Categories and weighting factors applied to each GIS layer

Layer	Nº categories	Weighting factor
Building volume	4	6
Building surf. fraction	6	6
Green areas	4	-4
Ventilation paths	4	-5
Slopes	3	-3

Fig. 4 shows Bilbao UC-AnMap including all the relevant climate aspects for urban planning. It shows up to seven categories of climatopes based on thermal comfort impact (from cold air production areas to high heated areas). Ventilation paths turn to be an important factor in Bilbao urban climate (i.e. air flow along the river crossing the urban area and thermal induced downslope winds during night-time). These air systems need to be preserved with the aim of mitigating the UHI. Additionally, strategic actions could be taken in the nearby areas to allow a wider influence of ventilation paths.

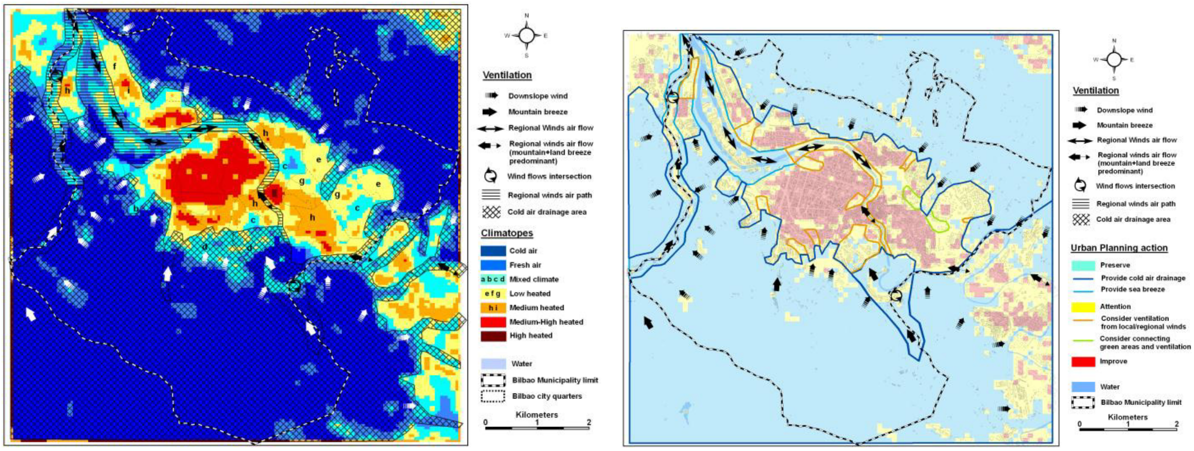

Fig 4. Bilbao UC-AnMap and UC-ReMap

Urban climate sensitivity zones were defined in the UC-ReMap (Fig.3) including relevant guidelines to urban planners. Three categories were defined:

- Areas to preserve: cold and fresh areas with good ventilation,
- Areas to attend climate: low thermal load areas where the effects of new developments should be evaluated,
- Areas to improve: areas where relief of urban heat load is needed and specific cooling actions should be considered together with an improvement in ventilation.

3.2. Measurements of thermal comfort levels

The results of the measurement campaigns in each of the four urban spaces were in agreement with the urban development characteristics and their location inside the urban area (influence of regional climate). These two factors affect thermal comfort levels and their temporal evolution. Levels perceived as 'very hot' (PET > 41ºC) were not common in the four selected areas during the campaigns. Most of the highest PET values occurred around midday and the first hours of the afternoon (i.e. 11:00 to 16:00 UTC) in sites exposed directly to sun radiation and are in the range of 'hot' (35<PET<41º). Highest PET values (Fig. 5) during this period of the day tent to be registered in *CascoViejo* and lowest in *Miribilla* in relation with their location inside the urban area and their specific urban development characteristics. On the other hand, sites under shadow influence only reached the 'slightly warm' level (Fig. 5), similar to the overcast day (i.e 8th August). Generally, thermal comfort during the first measurements in the morning was in the 'slightly cool' level (i.e. 13ºC < PET < 18ºC). At this time, the lowest registered PET value occured in *CascoViejo* at 7:00 on 7th August due to clear sky and the effect of night-time cooling. On the contrary, low dense clouds on the morning of 8th August caused 'neutral/comfortable' levels in CascoViejo. As expected, on direct solar radiation exposed sites, PET increased quickly during the morning hours. During the end of the afternoon, in the absence of direct sun radiation thermal sensation in all the areas was in the range of 'neutral/comfortable' except CascoViejo on 8th August. Again, in this case, low dense clouds were responsible for reducing urban heat loss and PET reached the 'slightly warm' level.

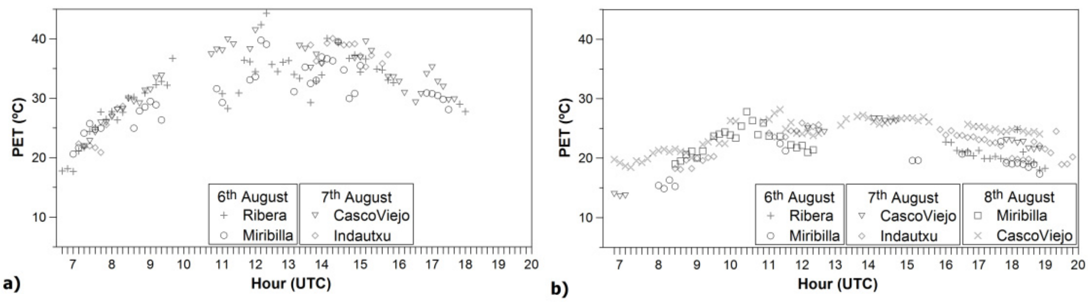

Fig. 5 Temporal evolution of PET for each area and selected day in a) direct sun exposed sites and b) shadow sites and overcast situation (i.e. null direct solar radiation)

Considering that measurements were carried out in typical summertime climate conditions, results were considered as representative of thermal perception levels in the selected areas during overcast conditions, partly covered and clear days.

3.3. Local micro-scale modelling

Contrary to discrete measurements of thermal comfort (section 3.2), results of modelling allowed evaluating the spatial distribution of thermal comfort levels in each area and showing the influence of building distribution and orientation, location of vegetation and characteristics of surface materials, together with the regional climate conditions affecting the specific area of the city. This was highlighted in the case of the clear day (7th August) in two different developed areas at 12:00 (UTC): *CascoViejo* and *Indautxu* (Fig. 6). Of course highest PET values (thermal comfort values) were registered in sites exposed to direct sun radiation. Highest values were registered in *CascoViejo*, while the influence of higher WS in *Indautxu* reduced thermal perception levels. Additionally, the presence of vegetation in *Indautxu* was also noticed in discrete points inside the urban square due to the effect of shadowing reducing thermal perception to comfortable levels at 12:00 (UTC) on a clear sky summer day.

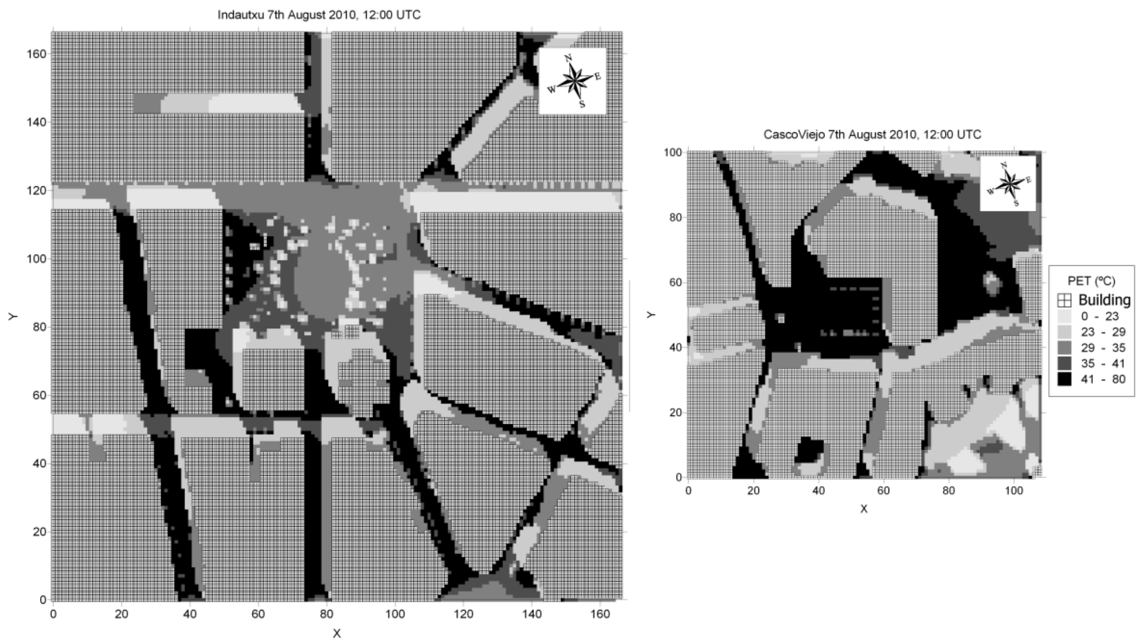

Fig. 6 Spatial distribution of PET levels in Indautxu (right side) and CascoViejo (left side) during a clear sky day in summer (7th August 2010) at 12:00 (UTC)

Thermal comfort modelling results showed differences with respect to measurements. Pearson's correlation coefficients between $PET_{measured}$ and $PET_{modelled}$ were not high (Table 3). Root mean square error (RMSE) including all days and areas was 5.93 ºC

Table 3 Pearson's correlation (r) for measured and modelled PET values considering each area and selected day, as well as for all data available.

Day	Area	Pearson correlation coefficient (r)
6th August	Ribera	0.833**
	Miribilla	0.802**
7th August	Indautxu	0.611**
	CascoViejo	0.678**
8th August	Miribilla	0.602*
	CascoViejo	0.761**
All days and areas		0.727**

** p<0.001
* p<0.01

Percentile 10th and 90th for all ΔPET ($PET_{modelled}$ - $PET_{measured}$) values is -5.2ºC and 9.4ºC respectively. Considering that ‖ΔPET‖ > 5-6 ºC causes relevant difference in thermal perception (Table 1), it turns out that simulated PET scenarios lacked reality at certain sites. Results showed two different climate patterns for ΔPET variability. On one hand, on partly covered or clear sky days ΔTmrt was the most relevant variable. On the other, on overcast days in the absence of direct solar radiation, model estimation of both WS and Tmrt played an important role in ΔPET values

4. Conclusions

During the last seven years urban climate studies at different spatial scale have been performed in Bilbao. On one hand, the UC-Map includes all the relevant climate information from the regional to the urban scale. However, when downscaling to local scales, the UC-Map is useless. To evaluate climate at scales from street to city quarter, further analysis at microscale analysis were carried out. Thus, it is important to remark that for complete and adequate urban climate considerations in urban planning a combination of analysis at different spatial scales (i.e. mesoscale and microscale) is mandatory.

The method used for the UC-Map was simple (5 GIS layers) and was proven to be suitable and adequate for urban planning purposes. Due to its simplicity, it can be exportable to many other urban areas and results are expected to be optimal.

On the micro-scale, modelling thermal comfort resulted with relevant difference with respect to measurements. Despite models like ENVI-met are frequently used and can provide aid for evaluating urban design scenarios caution should be taken if precise thermal comfort levels are to be derived from modelling results. In this case, measurements of climate variables inside the area of study would improve the assessment significantly.

Thus, for both UC-Maps and microscale climate modelling it is recommended to include specific measurement campaigns to validate results.

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